

ENGINEERING CASE LIBRARY

DIGGING INTO MARS II

One alternative considered at some length during design and development of the surface sampling system for the Viking mission to Mars was a mortar-launched canister. This could serve as a long-range and/or backup soil scoop. This case focuses on the analysis carried out by the engineering team during the design of the mortar-launched sampler.

(C) 1982 by the American Society for Engineering Education. Prepared by J. A. Alic at Wichita State University, January 1978, with the support of grant No. SER77-0245I from the National Science Foundation. The cooperation of the National Aeronautics and Space Administration, particularly Leonard V. Clarke of NASA-Langley, and of Martin Marietta Aerospace, Denver, in particular Donald S. Crouch, is greatly appreciated. The material in this case is drawn primarily from Martin Marietta Report TN-3770II2, "Backup Surface Sampler Study: Mortar-Launched Surface Sampler," by M. L. Clevett, W. C. Burkitt, and B. McKown, June 1971.

DIGGING INTO MARS II (A)

From 1969 through 1975, a group of Martin Marietta engineers under the leadership of Donald S. Crouch worked on the development of the surface sampler subsystem for the Viking mission to Mars. An overview of this effort is contained in a companion case study, "Digging Into Mars: The Viking Surface Sampler."* The present case concerns one small portion of the surface sampler project, taking place during a three month period in 1971.

The format of the case utilizes a series of Instructions, each posing problems or questions for the student to solve, while the following sections tell the actual course of events. As in any case study, there is no implication that the material presented is right or wrong. The case simply describes what the engineers working on the project did.

INTRODUCTION

The primary purpose of Viking was to carry out a series of scientific experiments in an attempt to determine whether or not life exists on Mars. For this purpose it was necessary to gather samples from the Mars surface--these might be rocks, sand, dust, or soil-like material--and deliver them to the experimental apparatus on the Viking lander. This is the function of the computer-controlled surface sampler acquisition assembly (SSAA).

Early in the program, a baseline design for the SSAA was established--a scoop on the end of a 10 ft retractable boom. The scoop would reach out, dig up a sample from the Mars surface, and carry it back to the lander. Many alternative SSAA designs were developed in parallel with the baseline 10 ft boom and scoop. Some of these alternatives were under consideration as backups to provide redundant sampling capability and hence greater reliability. Others were long-range samplers, capable of bringing back material from beyond the 10 ft reach of the boom. Such a long-range sampler might eventually become either a replacement for the baseline design or a supplement. The primary reason for looking at long-range samplers was the possibility that the exhaust gases from the rocket engines on the lander might contaminate the nearby soil. A secondary reason was simply the desirability of increasing the sampling area.

Whatever type of surface sampler(s) were included on Viking, they would have to function reliably after heat sterilization at 235°F and a subsequent flight of more than 300 days. On Mars, the temperatures would range from -135°F to +80°F, while winds of 200 mph were expected. Although these winds create violent dust storms, the atmosphere, consisting primarily of CO₂ (95%), has a pressure of only 5 millibars. Gravitational forces are less than 40% of those on Earth (g = 12.2 fps² on Mars).

In addition to the harsh operating environment, the SSAA would be limited in the amount of electrical power it could draw upon. Two radio-isotope thermal generators provide up to 70 watts of continuous power to the lander, with more peak power available from batteries. The batteries would be charged during periods of low power usage. Of course, there are many other systems on the lander besides the surface sampler which require power.

One of the long-range sampler concepts that the Viking SSAA engineering group considered was a mortar-launched, dragline retrieved sampler, illustrated in Exhibit 1. The sample collector is a tubular cannister, open at one end. This would be launched from a guide tube or barrel mounted on the lander. Reeling in a dragline attached to the projectile-collector would pull it back to the lander. The collector would scrape up material from the Mars surface until closed by a ball on the dragline. Upon reaching the lander, the projectile-collector would be drawn back into the muzzle of the launch tube, which had a rounded lip to guide it. The contents would then be dumped by gravity to the science experiments, leaving the empty collector in position to be re-launched for gathering more samples.

Various mortar-launched collectors of this type had been suggested in the past for other space missions; however, none had ever been used. Thus, the Viking engineering team had little in the way of previous experience to build upon. At the beginning of their work they established a preliminary set of design goals, several of which are listed below:

- weight: 10 lb or less.
- launch range: 100 ft minimum.
- repeatability: at least 8 launch and retrieve cycles.
- aiming capability: elevation and azimuth through 45°.
- control systems: fully automated.

While there were a number of other important aspects of the mortar-launched sampler--for instance, the design of the dragline take-up reel--this case study will focus on the launching of the projectile-collector.

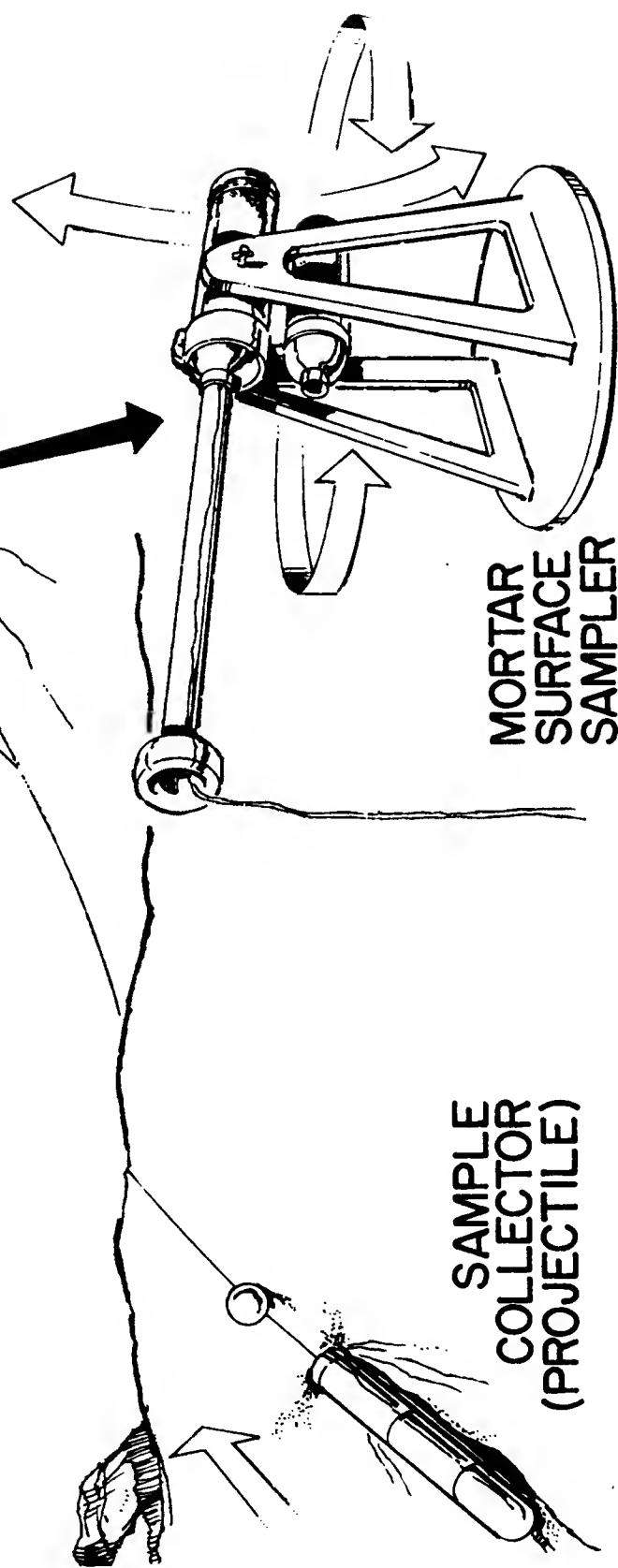
Instruction A

Think of as many ways as you can to launch the projectile-collector. From these, pick one or more--but not too many--which appear to be worth further study. Write a brief justification of your selection in terms of the design criteria discussed above, potential for development, etc.

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DIGGING INTO MARS II (B)

A portion of the report prepared at Martin Marietta to document the mortar-launched sampler project reads as follows:

Assuming that one must shoot, throw, sling or launch a small, one-fourth pound projectile-collector a minimum of 100 feet, there are a wide variety of mechanical, electrical, and chemical devices and techniques which are adaptable. However, since the Viking mission requirements for backup surface samplers are a highly unusual set of design guidelines, such devices as cross-bows, catapults, and black powder cannons were not given serious consideration as practical design approaches. In fact, it appeared to those who were involved in this study that there were only two basic launch concepts that might successfully be developed in the course of the 90-day project and still meet the basic design objectives. These two launch concepts were (1) mechanical spring, and (2) compressed gas.

Instruction B

Develop conceptual designs for launchers having as energy sources springs and compressed gas. These designs should be developed in enough detail so that the two concepts can be evaluated and compared. While you will need to explain how the designs work--with sketches and words--it is not necessary at this stage to prepare dimensioned drawings.

Work your designs out far enough to decide which concept is best. Then write a short memorandum (no more than two typed pages) to your instructor, imagining him or her to have the role of your supervisor at Martin Marietta. In this memorandum, you should propose a concept to be developed as a working prototype and estimate the time that will be required for this. A brief justification of your proposed conceptual design should of course be included. Your time estimate should be broken down to include (1) engineering time for further design and analysis; (2) drafting time to prepare sketches or drawings for construction of the prototype; (3) shop time for building the prototype; and (4) the time required for testing of the prototype.

The prototype can be envisioned as a breadboard or proof-of-principle model--that is a design built for preliminary testing and development aimed primarily at evaluating feasibility. Such a prototype would typically be built using off-the-shelf components wherever possible.

DIGGING INTO MARS II (C)

The Viking engineers chose to proceed with a gas-powered launcher because of two possible problems they foresaw with a spring-launch mechanism: (1) the possibility of the dragline becoming entangled with the spring(s), and (2) the high force levels required to cock a mechanical spring strong enough to give the desired range. These potential drawbacks of spring-powered launchers were confirmed during simple laboratory experiments.

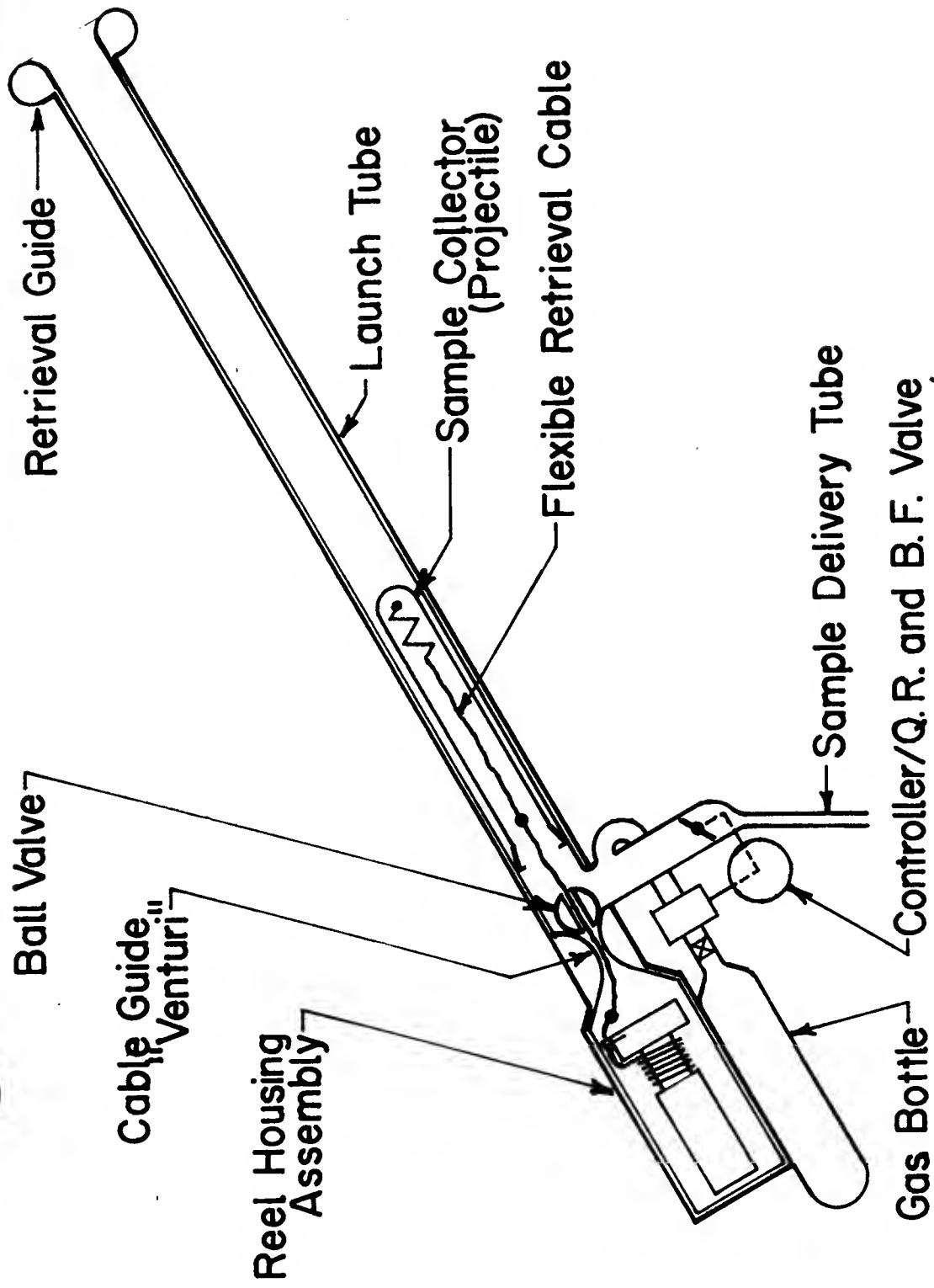
The gas-powered launcher was envisioned as a launch tube or barrel to which a small amount of high pressure gas would be admitted by a fast-acting valve. Expansion of the gas would launch the projectile-collector. The high pressure gas would be stored in a small tank. Exhibits C-1 and C-2 illustrate the conceptual design of the prototype.

Instruction C

Given that a gas-powered launcher design is to be pursued, it is necessary to choose a propellant gas. If you have not already done so in following one of the previous instructions, make a list of the considerations that you think are important in selecting a propellant gas (e.g., should not be an organic compound which might itself contaminate Mars). Then use this list to select a gas--or mixture of gases--to be used as the propellant.

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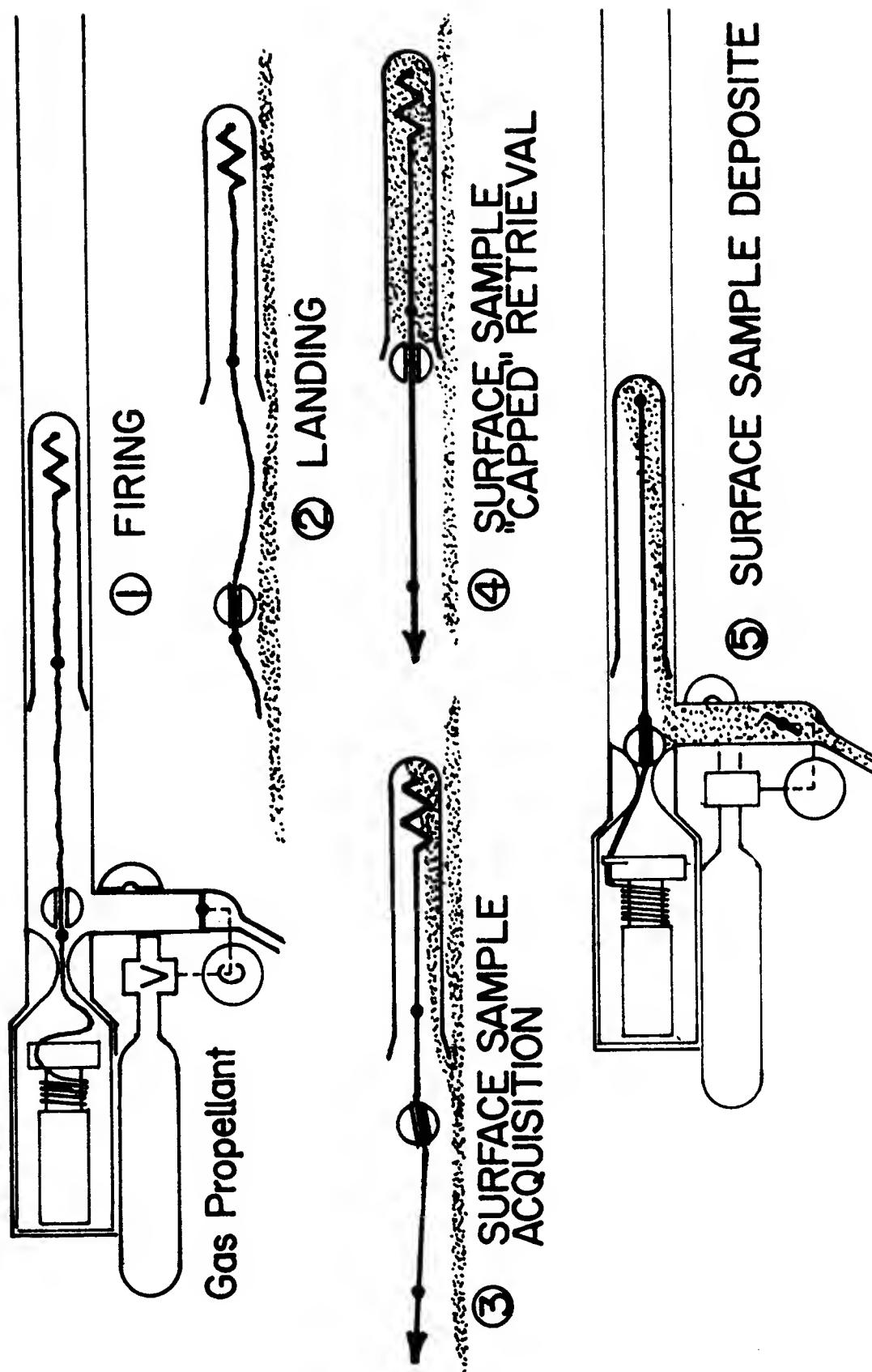


Exhibit C -2. Launch and Retrieval Sequence for Prototype Sampler.

DIGGING INTO MARS II (D)

Among the gases considered as propellants were helium, nitrogen, and carbon dioxide. Pressure-temperature diagrams for these gases are given in Exhibit D-1. CO_2 was selected for reasons outlined in the report excerpt quoted below.

- 1) CO_2 is a major constituent of the Martian atmosphere, so no contamination is introduced by firing the mortar;
- 2) It is readily maintained in the liquid phase by moderate pressure at the temperatures experienced in space or on the Martian surface. This minimizes storage volume;
- 3) Operating pressure of CO_2 may be maintained at a nominal value in the presence of surface temperatures expected on Mars which range from -135°F to $+80^{\circ}\text{F}$ by applying small amounts of heating power to the gas storage cylinder. No refrigeration, pressure sensing, or regulation are required for the proposed system. Further, no telemetering or on-board logic is required. Use of heating power could possibly be eliminated if sampling were limited to daylight hours.

Because the highest ambient temperature expected on Mars was about $+80^{\circ}\text{F}$, the corresponding pressure for CO_2 gas in equilibrium with liquid--900 psi (see Exhibit D-1)--was picked as the nominal operating pressure. Electric heating, as noted, could be used to raise the temperature to this level if necessary.

Instruction D

It was also important to verify that a gas pressure of 900 psi would be sufficient to propel the projectile-collector 100 ft or more. In order to find the relationship between projectile range and gas pressure, several parameters of the mortar design needed to be specified. These were chosen, rather arbitrarily, as follows:

- barrel length: 18 in.
- barrel inside diameter: 1 in.
- mass of projectile-collector: 1/4 lbm.

Find the relationship between projectile range and propellant gas pressure making whatever other assumptions may be necessary.

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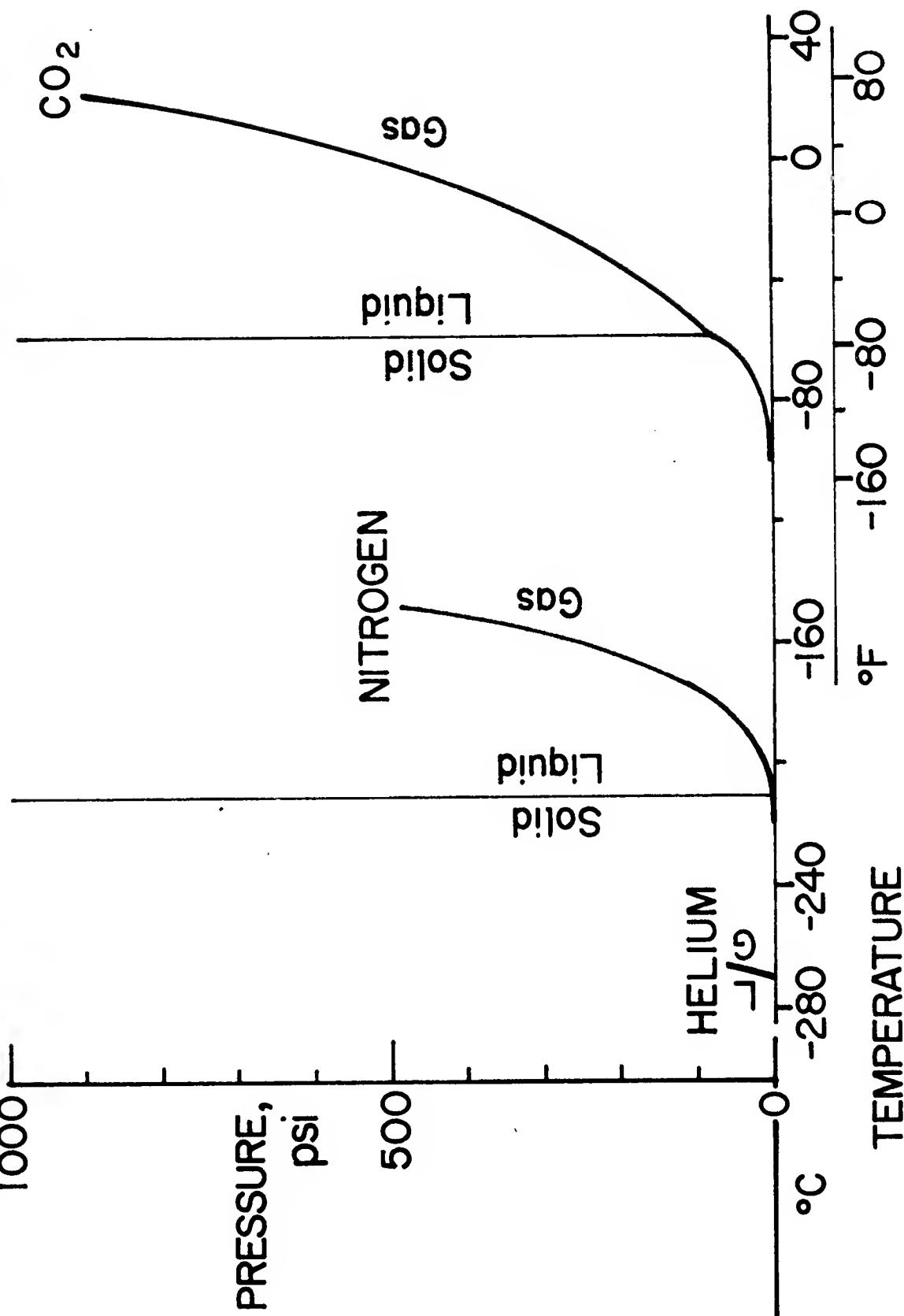
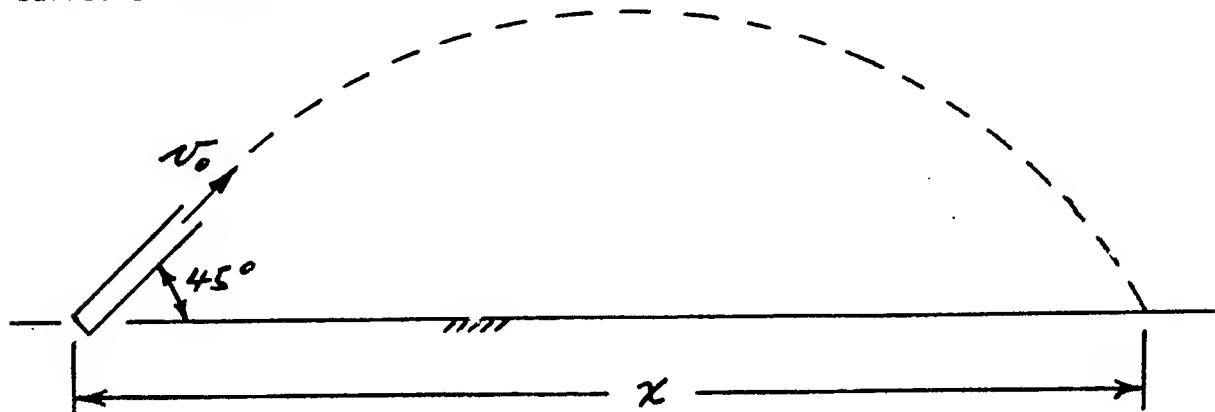


Exhibit D-1. Phase Diagrams for Possible Propellant Gases.

DIGGING INTO MARS II (E)

The Viking engineers performed their analysis for a range of 150 feet on Earth. This was because their objective at this stage of the project was to design a prototype mortar-launched sampler to be tested on Earth. However, they neglected air resistance in their calculations both for simplicity and because the atmosphere on Mars is so thin.

Maximum range in the absence of air resistance occurs for a 45° barrel elevation:



Then

$$x = \frac{v_0^2}{g}$$

where v_0 = initial projectile velocity, or $v_0 = \sqrt{gx}$. Using the value of g for Earth and a range of 150 ft,

$$v_0 = \sqrt{32.2(150)} = 69.5 \text{ fps.}$$

Because of the retarding force of the dragline which the projectile would pull behind it, the target v_0 was increased to 75 fps.

The Viking engineering team next used the principle of work and energy

$$W = \Delta E_k$$

to find the average gas pressure required for a v_0 of 75 fps. In this equation, W is the net work done on the projectile as it moves up the barrel, and ΔE_k is its change in kinetic energy--here simply equal to its kinetic energy when leaving the barrel, $mv_0^2/2$. Thus,

$$E_k = \frac{mv_0^2}{2} = \left(\frac{0.25}{32.2}\right) \frac{(75)^2}{2} = 21.8 \text{ ft-lb}$$

or

$$E_k = 262 \text{ in-lb} .$$

Calculation of the work done on the projectile required a further assumption. Friction between the projectile and the barrel was neglected on the basis that the projectile-collector would fit loosely in the launch tube so that blow-by of the expanding CO_2 would prevent metal-to-metal contact. Thus the work of the gas forces only was considered. However, these forces vary continuously as the projectile is accelerated and the gas pressure drops. Nonetheless it was easy to calculate the average gas pressure required, \bar{p} :

$$W = \bar{p} \ell A$$

where ℓ is the barrel length (18 in.) and A is the cross-sectional area of the projectile-collector.

$$W = \bar{p} \left[\frac{\pi(1)}{4} \right] (18) = 262 \text{ in-lb}$$

or

$$\bar{p} = 18.5 \text{ psig} .$$

This value is far below the supply pressure of 900 psi, giving an ample margin for varying the amount of gas admitted by the quick-opening valve. The 18.5 psi pressure is of course the pressure above atmospheric, since atmospheric pressure acts continuously on the nose of the projectile.

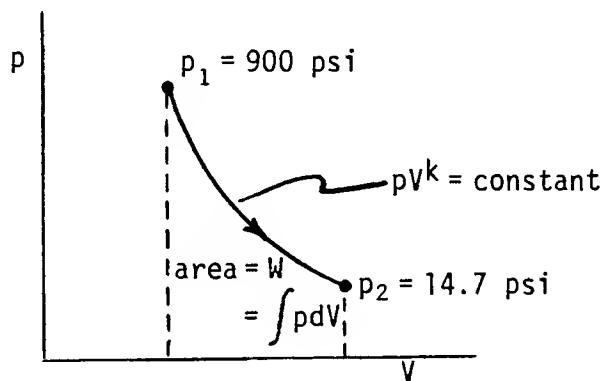
Instruction E

At this point, the engineers decided that they needed to know how much CO_2 would be used in launching the projectile-collector. Knowledge of the amount of gas expended per firing would give an idea of the size of storage tank required.

Calculate the amount of CO_2 required for a projectile range of 150 ft (on Earth).

DIGGING INTO MARS II (F)

To find the gas consumption, the Viking engineers analyzed the expansion process in more detail. They assumed the expansion within the launcher table to be isentropic (adiabatic and reversible), and the CO_2 to be an ideal gas. The gas was assumed to expand from 900 psi to atmospheric pressure (14.7 psi) at the barrel exit. The work process could then be shown diagrammatically as:



The volume V_2 in state 2 would be just the total barrel volume, or

$$V_2 = A\ell = \frac{\pi}{4}(18) = 14.1 \text{ in}^3 .$$

Although p_2 and V_2 are both known, the temperature T_2 is unknown. Thus, it was not yet possible to use the ideal gas law, $pV = mRT$, to find the mass m of CO_2 . However, because the process is isentropic, and $p_1V_1^k = p_2V_2^k$ (k = specific heat ratio, c_p/c_v), it is easily shown that

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}$$

With $T_1 = 80^\circ\text{F}$, or 540°R ,

$$T_2 = 540 \left(\frac{14.7}{900}\right)^{\frac{1.3-1}{1.3}} = 209^\circ\text{R} \text{ or } -251^\circ\text{F}.$$

Then, using the gas constant for CO_2 , $R = 35.1 \text{ ft-lbf/lbm-}^{\circ}\text{R}$, the mass of CO_2 is just

$$\begin{aligned} m &= \frac{p_2 V_2}{R T_2} \\ &= \frac{14.7 (144) \left(\frac{14.1}{12^3} \right)}{35.1 (209)} \\ &= 2.35 \times 10^{-3} \text{ lbm} . \end{aligned}$$

This is about 1 gm of gas. A bottle holding 187 gm of liquid CO_2 was used for the prototype. Later, tests showed that about 175 shots could be achieved before the bottle had to be refilled.

Instruction F

The launch tube was to be made of 6061-T6 aluminum alloy, as were many of the other parts of the prototype--and indeed of the Viking lander itself. The engineers needed to know if their planned barrel thickness of 1/8 in. was adequate. You should now estimate the stresses in the barrel when the mortar is fired.

DIGGING INTO MARS II (G)

In their final report, the design team outlined their barrel stress calculations as follows:

...it was shown that an average pressure in the barrel is 18.5 psi to attain the desired range under earth conditions. In the operation of the mortar, a metered volume of 900 psi CO₂ is suddenly released into the space behind the projectile, which begins to move up the barrel allowing the gas to expand to many times its original volume, with a resulting decrease in pressure.

It is unlikely that the barrel tube will experience the full 900 psi since the original volume of gas must first expand to fill the connecting tubing and the space behind the projectile. However, to ensure a conservative estimate, the 900 psi times a dynamic factor of 2.0 is used as a design pressure.

Assuming a thin-walled pressure vessel, the circumferential stress was then calculated as

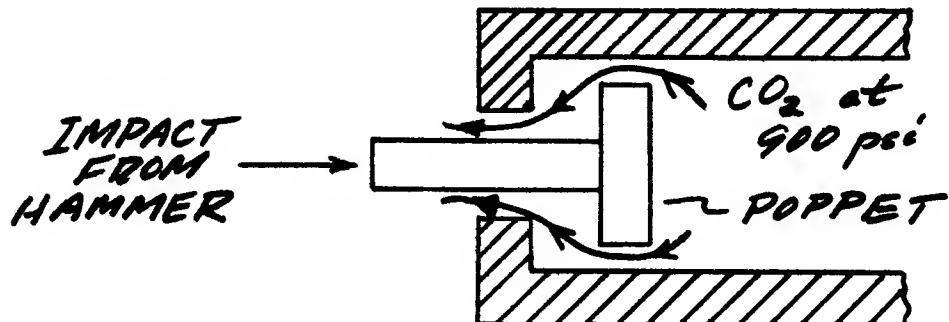
$$\sigma = \frac{pR}{t} = \frac{900(2)(1/2)}{1/8}$$

$$= 7200 \text{ psi}$$

This stress is small compared to the 40,000 psi yield strength of 6061-T6 aluminum alloy.

Instruction G

The next problem that the design team attacked was the quick-opening valve for admitting CO₂ into the launch tube. This valve was conceived as a poppet which would normally be held closed by the gas pressure:



To fire the launcher, the spool of the poppet valve would be struck by a sliding hammer. The hammer was to be driven by either a spring or a solenoid. The impact would open the valve momentarily, allowing high pressure gas to flow through a tube to the barrel. Then the valve would be closed again by the gas pressure. A plastic valve seat would be used to ensure a good seal.

The engineering team decided to perform a dynamic analysis of the poppet motion in order to find the best way of varying the time the valve remained open. This would determine the amount of gas released and hence the range of the projectile-collector. The purpose of the analysis would be to determine how the parameters of the valve and hammer system--e.g. hammer mass, valve mass--affected the time the valve remained open.

Perform such an analysis.

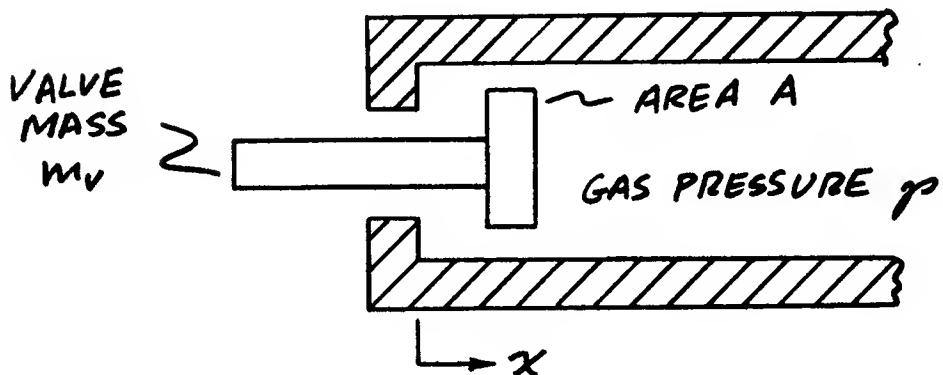
DIGGING INTO MARS II (H)

The Martin Marietta engineers began their analysis of the valve dynamics by writing Newton's second law for the valve poppet:

$$F = ma$$

or

$$(-)pA = m_v \ddot{x}$$



They assumed that, when the mortar was fired, the hammer blow would give the valve an initial velocity v_0 . That is

$$\dot{x} = v_0 \text{ at time } t = 0.$$

Then the valve motion is given by

$$\ddot{x} = -\frac{pA}{m_v}$$

Integrating,

$$\dot{x} = -\frac{pA}{m_v} t + v_0.$$

The valve has its maximum displacement when its velocity falls to zero

$$\dot{x} = 0 = v_0 - \frac{pA}{m_v} t$$

at time

$$t = \frac{m_v v_0}{pA}$$

The valve then returns to its seat with the same forces acting; thus the return time is the same. The total time the valve is open is then

$$t_{\text{open}} = 2 \frac{m_v v_0}{pA}$$

For a particular valve (fixed m_v and A), the initial velocity v_0 determines this time and hence the amount of gas that flows out.

The engineers concluded that the open time would be controlled by the hammer striking the valve and producing a particular v_0 . This was treated as a collision problem, in which momentum is conserved. Letting the hammer have a mass m_h and velocity v_h at impact:

$$m_h v_h = m_v v_0 + m_h v_h'$$

for a perfectly elastic impact. Here v_h' is the (unknown) hammer velocity after impact. If the collision can be characterized by a coefficient of restitution e , then v_h' can be eliminated. For this situation, e is defined by

$$e = \frac{v_0 - v_h'}{v_h}$$

so that $v_h' = v_0 - ev_h$ or $m_h v_h' = m_h(v_0 - ev_h)$. This expression was then substituted into the momentum equation, giving

$$m_h v_h = m_v v_0 + m_h(v_0 - ev_h) ,$$

which can be written

$$v_0 = \frac{m_h v_h (1 + e)}{m_h + m_v} .$$

From this, the Viking engineers concluded that the best way to control the amount of CO_2 released was by varying the hammer velocity v_h . This

they planned to do by using a spring-loaded hammer with a variable stroke cocking device. This would change the amount the spring was compressed and hence change v_h .

A second type of hammer was also designed, this one using a specially-wound solenoid to accelerate the hammer. However, this device was not completed in time for the testing program, and all tests on the prototype launcher were carried out with the spring loaded hammer.

Instruction H

As pointed out previously, on Mars the CO_2 pressure vessel would have to be heated to keep the pressure at 900 psi. This could be done by an electrical resistance heater, which might be controlled by a thermostat to keep the CO_2 at 70° to 80°F . Heat would be needed only prior to sampling operations and then only if the ambient temperature was lower than this. It was considered unlikely that launcher operations would take place at temperatures below -140°F . The engineers planned to insulate the CO_2 container to reduce heat loss, but the thickness of insulation was limited to 1 in. by packaging considerations. The pressure vessel would have a 3 in. outside diameter and be 1 ft long.

Pick an appropriate insulating material for this application and estimate the electrical power required for the heater.

DIGGING INTO MARS II (I)

A particular insulation was not actually chosen at this time. However, for purposes of this calculation the engineering group used a thermal conductivity k of 0.02 Btu/hr-ft-°F. This value would be representative of, for example, fiberglass batting, which being inorganic and heat sterilizable, would be appropriate for use on the launcher.

The heat transfer analysis was restricted to a calculation of conduction through the insulation, using the well-known equation for a hollow cylinder:

$$q = \frac{2\pi k \ell (T_1 - T_2)}{\ln r_2/r_1}$$

where ℓ = length of cylinder, r = radius of cylinder, and subscripts 1 and 2 refer to the inside and the outside of the cylinder. For the CO₂ bottle,

$$q = \frac{2\pi(0.02)(1) [80 - (-140)]}{\ln\left(\frac{2.5}{1.5}\right)} = 54 \text{ Btu/hr}$$

This is (approximately) equal to the worst case heat loss that would have to be made up by the electric heater, which would then need to supply

$$54 \text{ Btu/hr} \times 0.293 \text{ watts/Btu/hr}$$

or about 16 watts. Since heating would only be required intermittently, a 16 watt power consumption was not considered unreasonable.

After the preliminary design phase described in the preceding sections, a breadboard prototype of the mortar-launched sampler was built. This prototype is shown, ready for test firing, in Exhibit I-1. The horizontal tube below and perpendicular to the barrel contains the spring-loaded hammer for firing the mortar. A lever on the tube cocks the hammer. Thirty pound test fishing line was chosen for the dragline, which was pulled in by a modified fishing reel driven by an electric motor (not visible in the photograph).

Excerpts from the concluding sections of the report on the mortar-launched sampler are quoted below.

Considering the potential danger to personnel from testing the experimental mortar in the laboratory, all testing was conducted in the field. Over 100 launch tests were made during the final development stages of the conceptual model. Retrieval of surface samples was made in conjunction with about 15 of the launches.

During the first two tests, 300 psi gas pressure was used, but in all of the remaining tests the full 900 to 1000 psi CO₂ gas pressure was used. The decision to use the full cylinder pressure eliminated the need for a pressure regulator.

VII. TEST RESULTS

In general, test results indicated that the concept of a mortar-launched surface sampling system for Viking is practical.

Specifically, the following listed factors were determined through test:

- 1) Average firing range - 150 feet;
- 2) Maximum firing range - 350 feet;
- 3) Average CO₂ gas consumption/shot - 1 gram;
- 4) Average launch/retrieval cycle time - 3 minutes;
- 5) Average sample acquisition/cycle - 12 c.c.;
- 6) Electric power consumption/cycle - 2 watt-hours;*
- 7) Optimum operating gas pressure - 900 psi (@ 70°F);
- 8) Optimum dragline retrieval speed - 1 ft/sec;
- 9) Best dragline material - Dacron multifilament;
- 10) Optimum projectile-collector weight - 0.25 pound;
- 11) Optimum reel rotational velocity - 275 rpm.

IX. CONCLUSIONS AND RECOMMENDATIONS

The mortar-launched surface sampler concept that was designed, fabricated, and tested under this study is a feasible backup system to the primary Viking surface sampling system.

It is recommended that a more advanced flight-prototype mortar system be developed to meet the following preliminary specifications:

A. Mortar Weight

1) Gas Cylinder	0.5 lb
2) Insulation & Heater/Controls	0.25
3) Valves & Plumbing	0.5

* For motor-driven take-up reel only.

4) Retrieval Mechanism	0.5
5) Retrieval Gearmotor	1.0
6) Azimuth & Elevation (Gimbal) System	2.75
7) Barrel	0.5
8) Automatic Control System (Firing, etc.)	1.5
9) Projectile-Collector & Dragline	<u>0.5</u>
	Total Mortar Weight
	8.0 1b

- B. Maximum Firing Range - 50 meters
- C. Dragline Retrieval Velocity - 1 ft/sec
- D. Operating Gas Pressure - 900 psi
- E. Gas - CO₂
- F. Dragline Material - Dacron, 30-1b test
- G. Cycle Time - 3 minutes
- H. Launches per Mission - 12
- I. Average Sample Acquisition per Cycle - 20 cc
- J. Electric Power Consumption per Cycle - 3 watt-hours
- K. Launch Tube Material - Aluminum Alloy
- L. Electric Motors - same as Baseline Sampler Motors

It is estimated that a reliable, efficient prototype of flight hardware configuration can be developed within six months after go-ahead.

Despite these recommendations, development of the mortar-launched sampler was not continued. The primary reason was a redesign of the rocket engine nozzles on the Viking lander. The redesigned nozzles ended the concern over contamination of surface material around the lander which had been the primary reason for studying long-range samplers. Because of weight problems, the only back-up sampling capability on Viking is a set of passive collectors for trapping wind-blown dust. These, and the other alternate and redundant samplers which were studied, are described in more detail in "Digging Into Mars: The Viking Surface Sampler." Ultimately, back-up samplers were not needed, as the primary samplers--10 foot furlable booms carrying scoop and back-hoe--functioned successfully on both of the Viking landers. In fact, as of September 1978, both samplers remained operational after more than 2 years on Mars.



Exhibit I-1. Prototype Mortar-Launched Surface Sampler.